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Nuclear Weapon Fundamentals and Development History

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Los Alamos National Laboratory

November 25, 2020

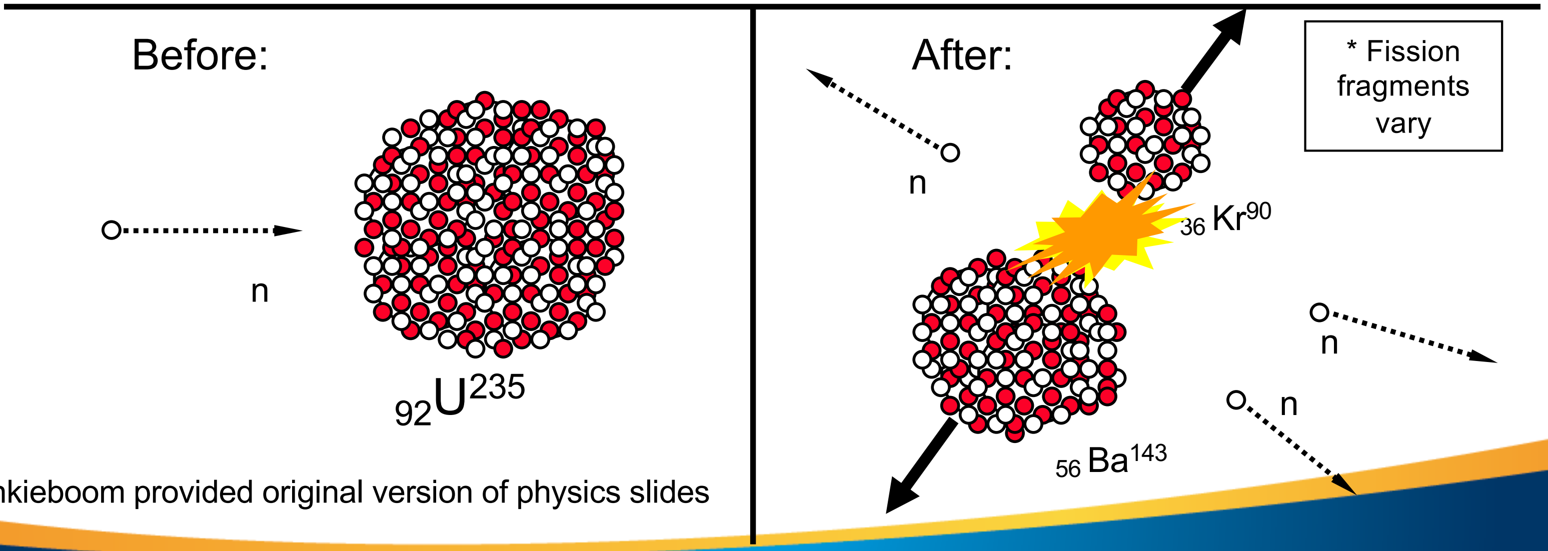
For Tarrant County College symposium

Outline

1. Review of nuclear physics
2. Fission weapons (WW2 and aftermath)
3. Weapon Effects
4. Fusion physics, boost, and the hydrogen bomb
5. Weapon development history – 1950's
6. Project Plowshare
7. Modern weapons: the "Triad"
8. Thoughts on current situation and conclusions

What is Fission? (neutron-induced)

- One of many possible reactions that can occur when a neutron interacts with a ^{235}U nucleus
- Large energy release per reaction
- Additional neutrons released (opens possibility of a fission chain reaction)



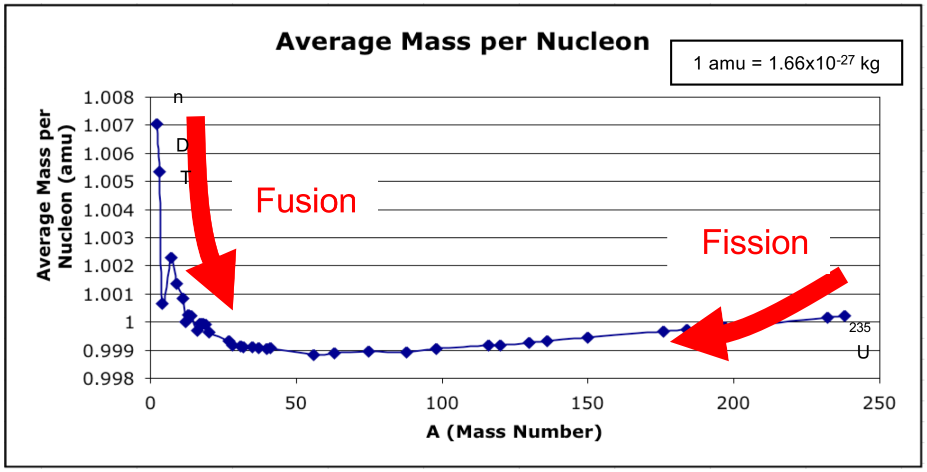
* Fission fragments vary

J. Vandenkieboom provided original version of physics slides

Fission energy release: mechanism

Einstein's Relation:
mass-energy equivalence
$E = mc^2$

For ^{235}U fission - mass of reacting nuclei is greater than the mass of the product nuclei.



$^{235}\text{U} + \text{n} \rightarrow {}^{236}\text{U} \rightarrow 2\ \text{FPs} + 3\text{n}$

Mass before = (236 nucleons)(1.0002 amu/nucleon)
= 236.05 amu

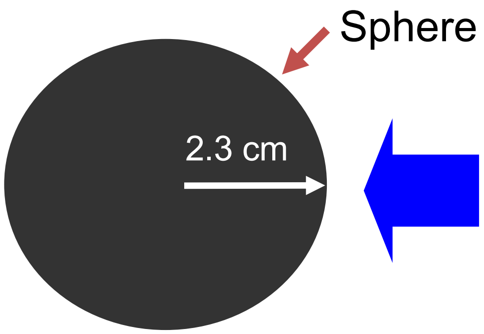
Mass after = (233 nucleons)(0.9992 amu/nucleon)
+ (3 nucleons)(1.0087 amu/nucleon)
= 235.83 amu

Mass Change = 0.22 amu
= 3.7×10^{-28} kg

Energy Release = 205 MeV

Fission releases much more energy than chemical

	Energy/Reaction	Energy density*
Combustion (Chemical)	4 eV	4.1 x 10^{4} J/cm^{3}
Fission	200 MeV	1.5 x 10^{12} J/cm^{3}



	Energy Available*	100 Watt (J/s) bulb would burn for:
72 g coal	2.2 x 10^{6} J (~1 lb. TNT)	~6 hours
or		
1 kg U	80 x 10^{12} J (19 kt TNT)	~25,370 years

* Complete combustion or fission is assumed

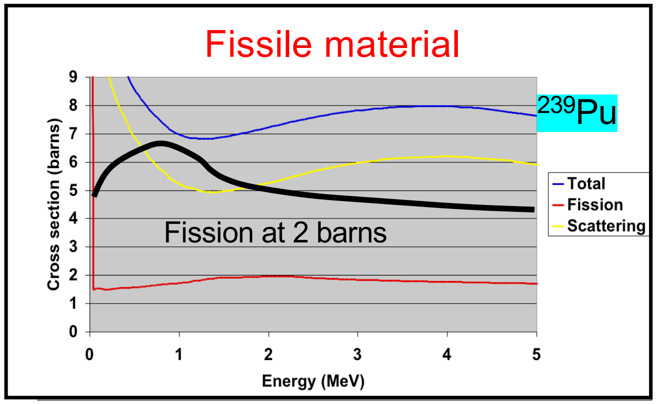
Nuclear timescales are faster than hydrodynamic

- High explosive detonation waves have speeds around 8 km/s (8 mm/μs), and can drive metal plates at speeds up to 4 km/s (4 mm/μs)
- An average bomb (~800 mm long) would take ~100 μs to explode

- Neutron population time behavior is conveniently approximated as a series of successive generations: (Gen 1: N_o neutrons, Gen 2 $N_1 = kN_o$ neutrons; Gen 3: $N_2 = kN_1 = k^2N_o$ neutrons, and so on
- For fast (>1MeV) neutrons, time between generations is ~10^{-8} sec = 1 shake
- 1 kton = 1.45×10^{23} fissions; happens in 0.51 μs; 100 kt in 0.58 μs

Nuclear timescales are much faster than hydrodynamic!

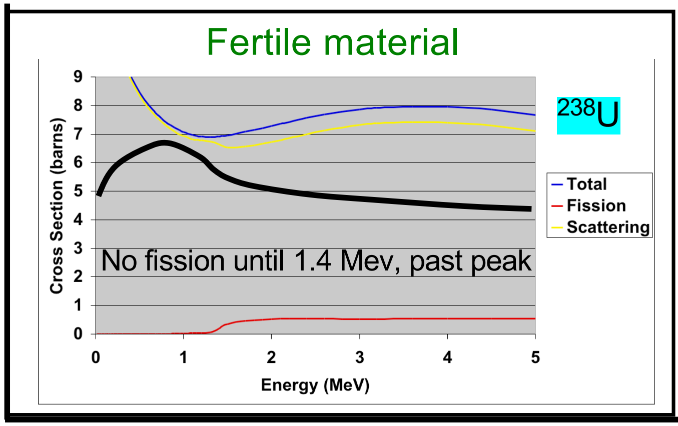
Neutron cross sections determines fissibility



Fissile material

^{239}Pu

Fission at 2 barns

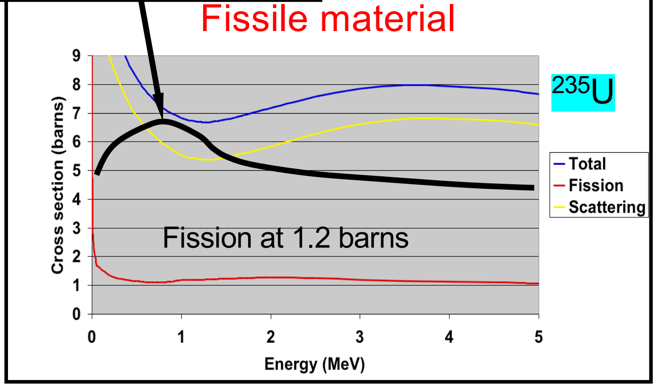


Fertile material

^{238}U

No fission until 1.4 Mev, past peak

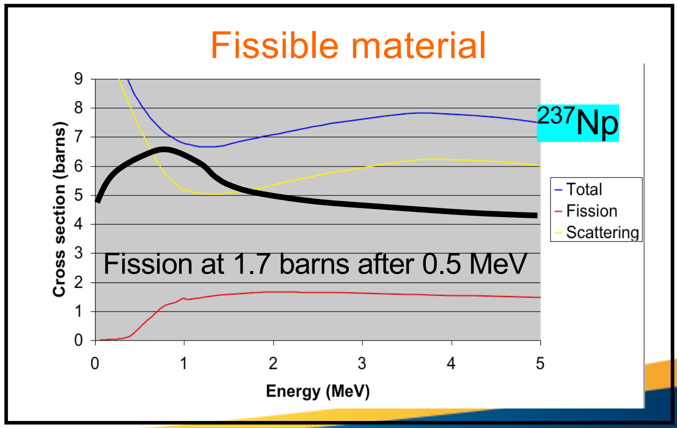
Fission neutron spectrum



Fissile material

^{235}U

Fission at 1.2 barns



Fissible material

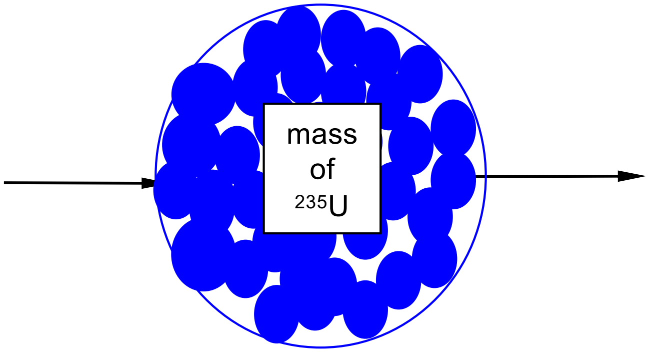
^{237}Np

Fission at 1.7 barns after 0.5 MeV

1 barn = 10^{-24} cm^2

Criticality - definition

Criticality - measure of how the number of neutrons (and energy release) in the system (e.g., reactor or nuclear weapon) will change over time



At $t = 0$, N_0 neutrons are produced by F_0 fissions

A short time later, at $t = \tau$, N_1 neutrons are produced by F_1 fissions resulting from these N_0 neutrons

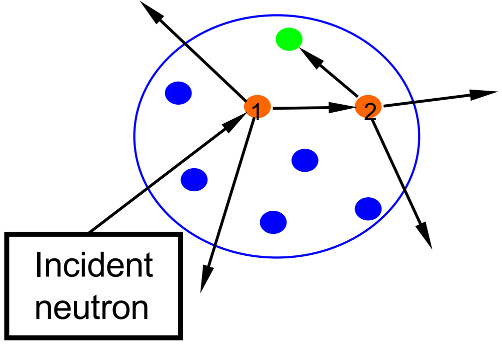
Multiplication Factor (k):

$$k = \frac{\text{\# of fissions in one generation}}{\text{\# of fissions in preceding generation}} = \frac{F_1}{F_0} = \frac{N_1}{N_0}$$

Criticality -- examples

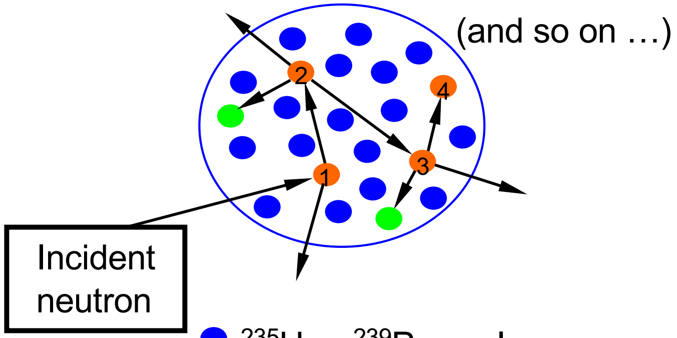
$k < 1$

Subcritical system: number of neutrons (and energy release) decrease with time



$k = 1$

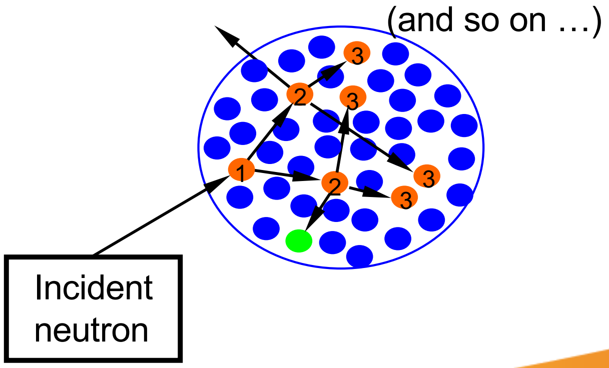
Critical system: number of neutrons (and energy release) constant with time



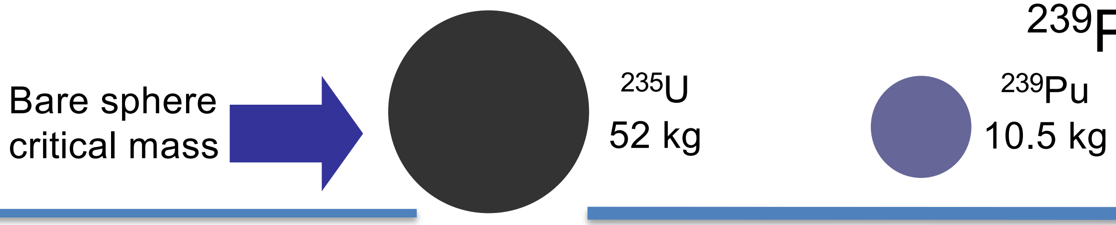
🔵 ^{235}U or ^{239}Pu nucleus
🟠 fission
🟢 neutron capture

$k > 1$

Supercritical system: number of neutrons (and energy release) increase with time



Material, mass, density affect criticality

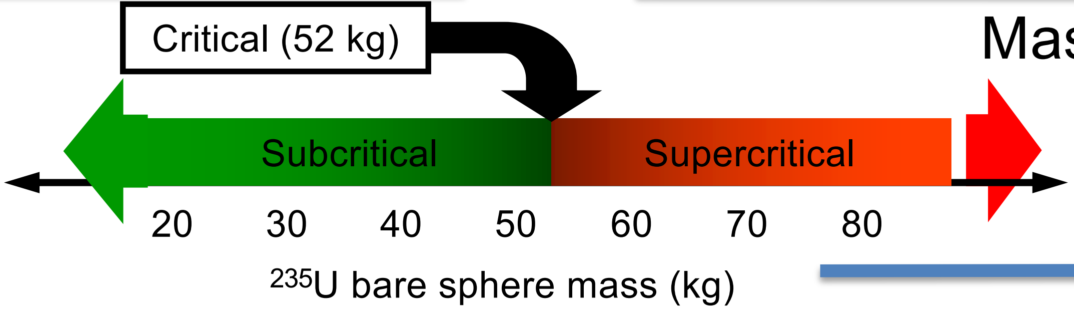


Bare sphere critical mass

^{235}U 52 kg

^{239}Pu 10.5 kg

^{239}Pu has a smaller critical mass compared with ^{235}U



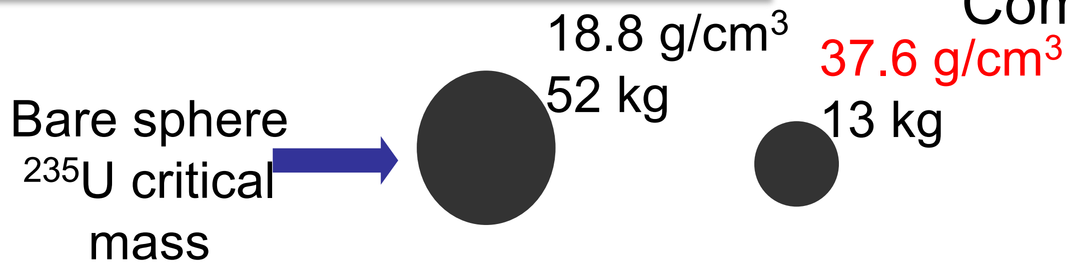
Critical (52 kg)

Subcritical

Supercritical

^{235}U bare sphere mass (kg)

Mass – for a given shape and density, a larger mass of material has a higher criticality



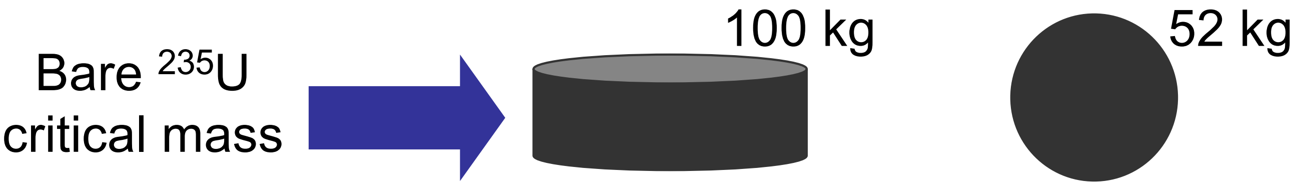
Bare sphere ^{235}U critical mass

18.8 g/cm^3
52 kg

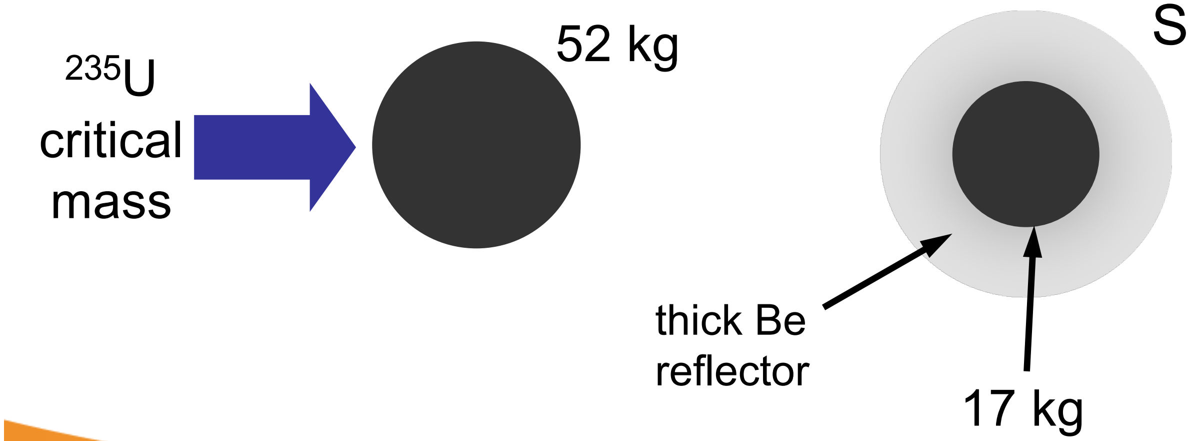
37.6 g/cm^3
13 kg

Compression – increases in material density result in smaller critical mass

Criticality also affected by shape and surroundings



Shape – for a given volume, shapes with smaller surface area have a smaller critical mass; sphere is optimal



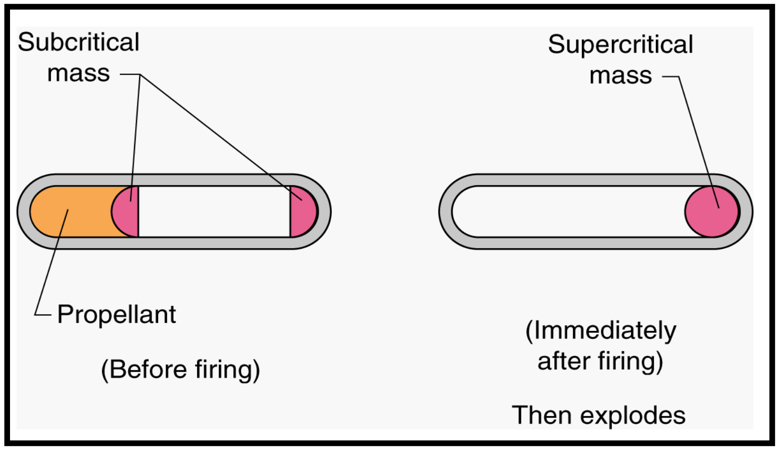
Surroundings--Surrounding a mass with a strong neutron reflector → results in a lower critical mass

Fission weapons

- A system for rapidly transforming a mass of ‘explosively fissionable material’ from a subcritical configuration to a highly supercritical configuration
- Initiation of a runaway neutron chain reaction while in supercritical configuration (need to inject neutrons at the right time)
- Maintain supercritical configuration long enough to allow large fission energy release

Gun assembly – first idea

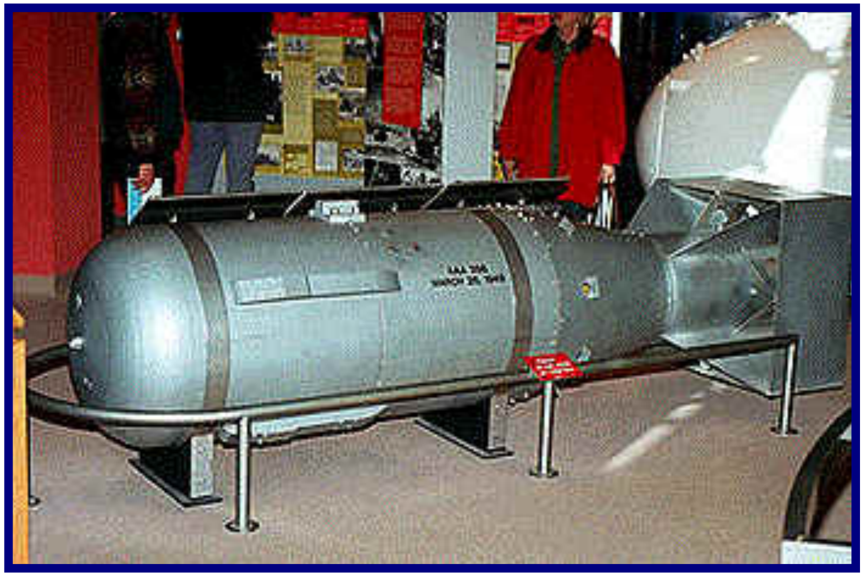
- Simple design
- Assemble subcritical masses together into a supercritical mass using propellant
- Inefficient use of material
- Slow assembly time necessitates use of a material with a very low neutron background (e.g., ^{235}U) to avoid pre-initiation; plutonium is precluded

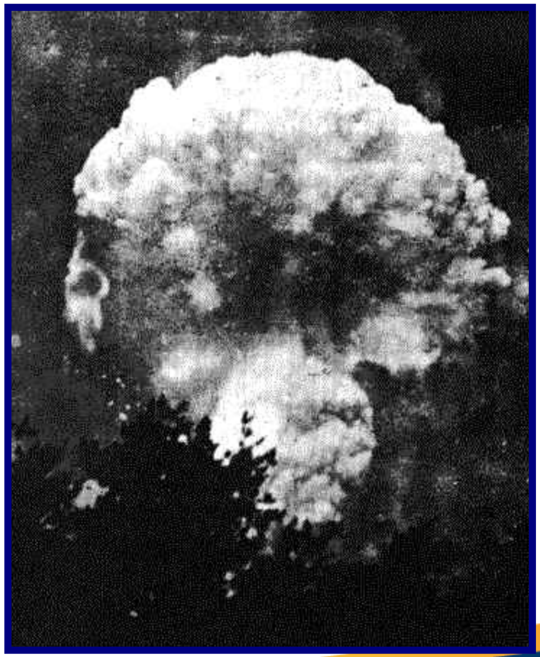


Compare:
HEU : ~1 neutron/kg/second
WGPu : ~60,000 neutrons/kg/second

Little Boy – simple, but effective

Untested prior to being dropped over Hiroshima on August 6, 1945 (15 kt)

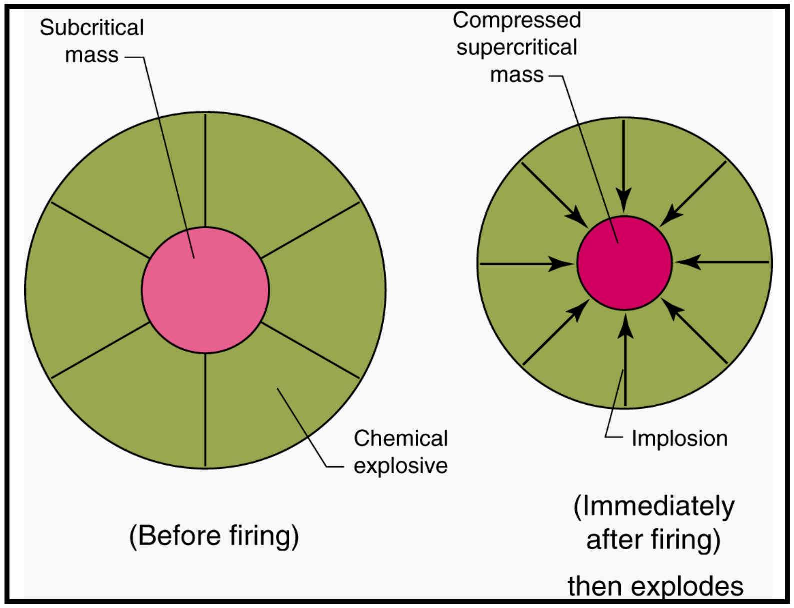




About 28” diameter, 10 feet long, 9,700 lbs

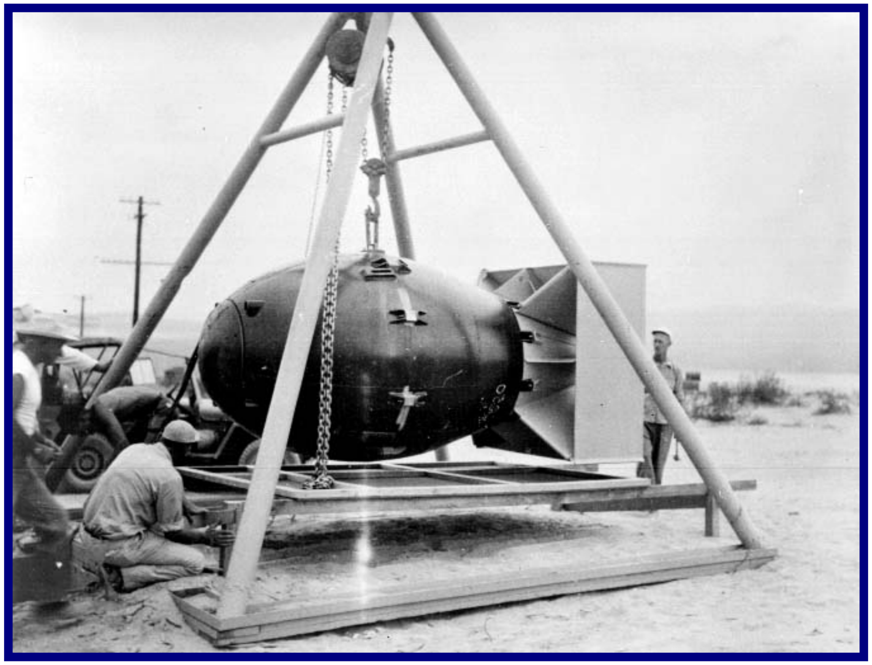
Implosion assembly – a way to use Pu

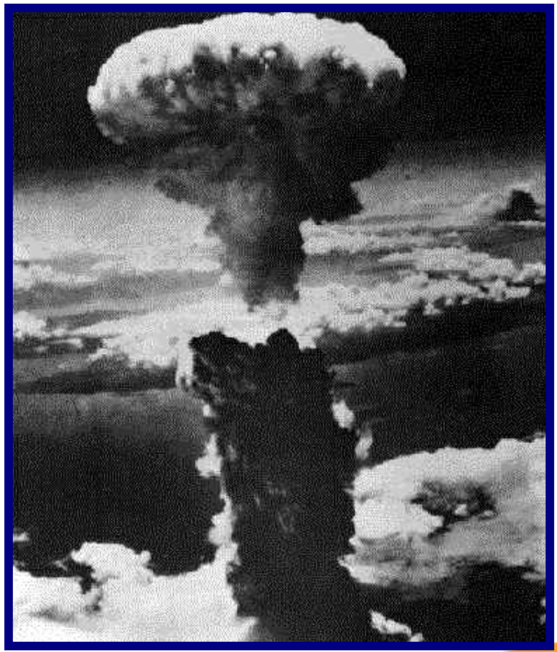
- Complex design – involves precision application of high explosive (HE)
- Symmetrical explosion of the HE implodes pit, compressing fissile material into a supercritical configuration
- More efficient use of material than gun-assembled weapon
- Fast assembly speed allows use of plutonium



Fat Man – first implosion bomb

Tested in Trinity shot 7/16/45 at Jornada del Muerto; dropped over Nagasaki on 8/9/45 (21 kt)





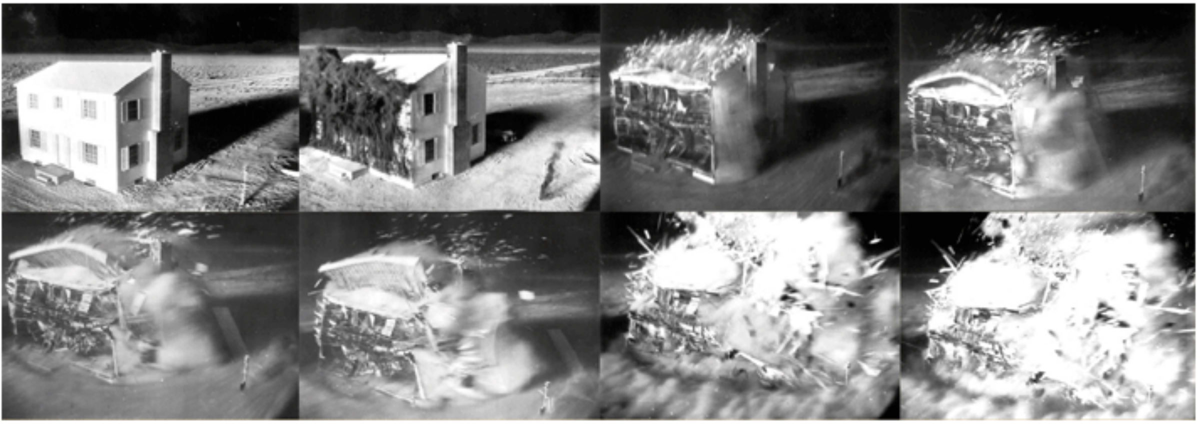
About 60” diameter, 10 feet long, 10,300 lbs

Post WWII: smaller, lighter, and safer

- Initial weapons had to be rushed out
- They were big and heavy – potential safety issues
- After WW2, push to make them smaller, lighter, and safer to use
- Also an interest in weapons effects
- There was still the interest in fusion weapons….

Effects of nuclear weapons

- Nuclear weapons have several types of output
  - Blast
  - X-rays and γ-rays
  - Neutrons
  - EMP



Apple II: shock wave destroys a house

Teak shot at 77 km

Kill Soviet armor

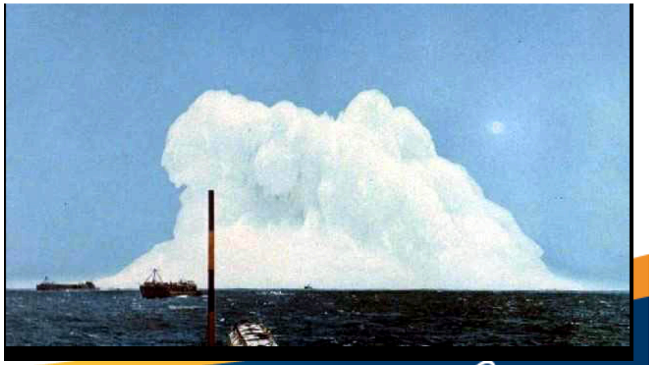
Weapon effects: underwater bursts

Able and Baker – effect of atom bomb on ships

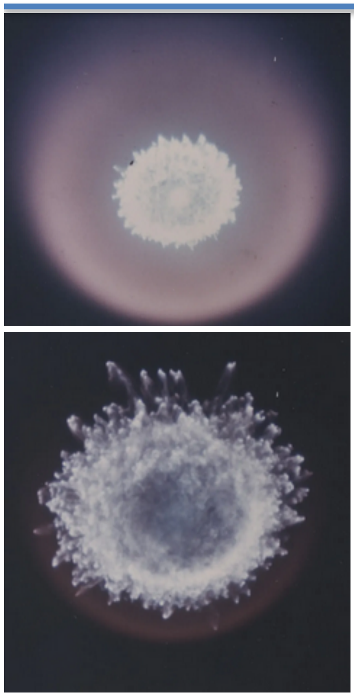
Due to inability to clean radioactivity, Charlie was cancelled

Wahoo:
deep
water
~500 feet
In 3200 feet

Wigwam:
deep
water
2000 feet
in Pacific



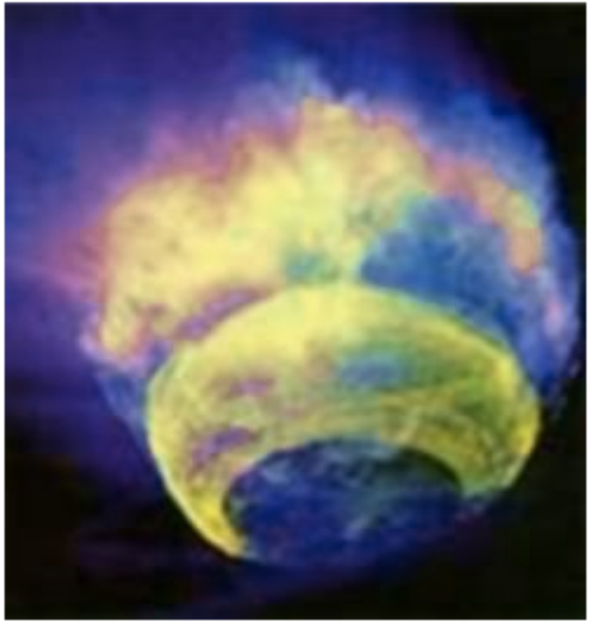
Weapon effects: high altitude



Checkmate
Low yield
10’s km up

Starfish prime test: 1.4 Mt at 400 km up. Damaged electronics in Hawai’i. Killed 3 satellites and damaged others. Led to cancellation of another test (repeat at 1000 km)

A Soviet test was ~300 kt at 290 km: it fused electronics, set a power plant on fire



Orange: 3.8 Mt at 43 km
Flash seen in Hawai’i,
but no EMP

1949: Soviets have the bomb and shocks US

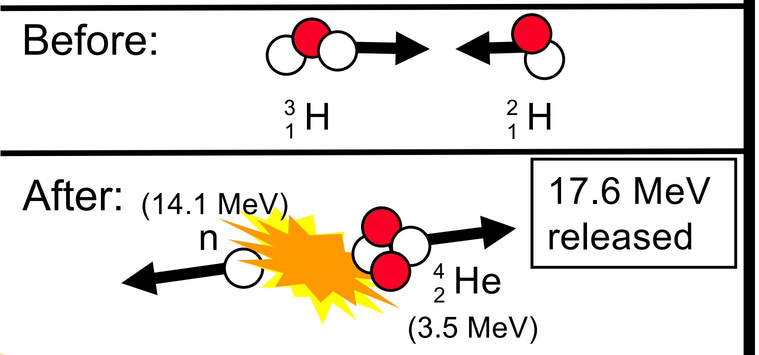
- The test of Joe-1 29-8-49 (which was a Soviet copy of “Fat Man”) was a shock to the US
- This spurred the development of more fission bombs and also thermonuclear weapons “hydrogen bombs”
- The “Cold War” was on
- Several episodes where US thought they were “behind” the USSR in the 1950’s

Hydrogen bombs use fusion reactions

- Can be thought of as the opposite of fission
- High temperatures (“thermonuclear”) and densities needed for reaction to proceed
- Large energy release per reaction
- High-energy neutrons can be released
- Far more yield per kg of material than fission

Example: ${}^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + n$

($T + D \rightarrow {}^{4}_{2}\mathrm{He} + n$)



Other reactions of interest:

$D + D \rightarrow {}^{3}_{2}\mathrm{He} + n + 3.2\ \mathrm{MeV}$

$D + D \rightarrow T + p + 4.0\ \mathrm{MeV}$

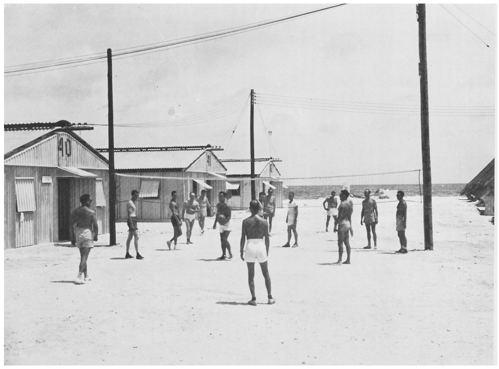
$D + {}^{3}_{2}\mathrm{He} \rightarrow p + {}^{4}_{2}\mathrm{He} + 18.3\ \mathrm{MeV}$

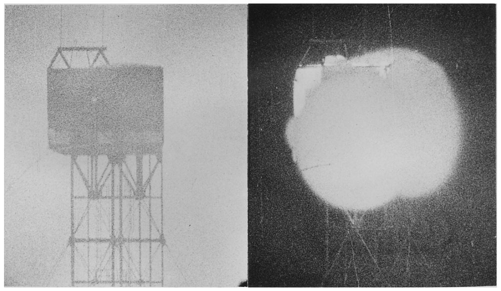
$T + T \rightarrow {}^{4}_{2}\mathrm{He} + 2n + 11.3\ \mathrm{MeV}$

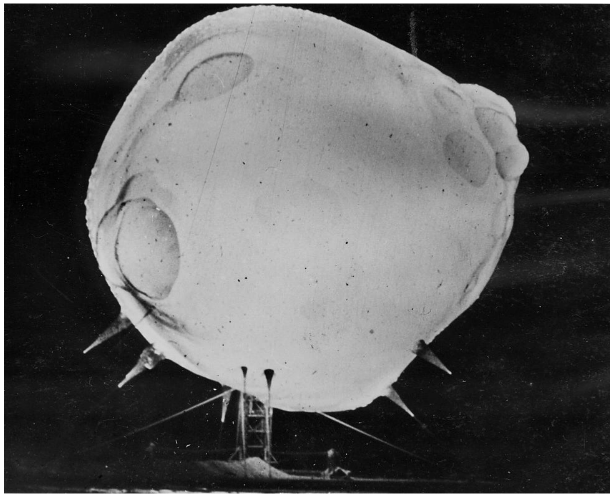
Greenhouse/Item –First US boosted device

Test 05/24/1951

Yield – 45.5 kt







Lithium can be used to “breed” tritium

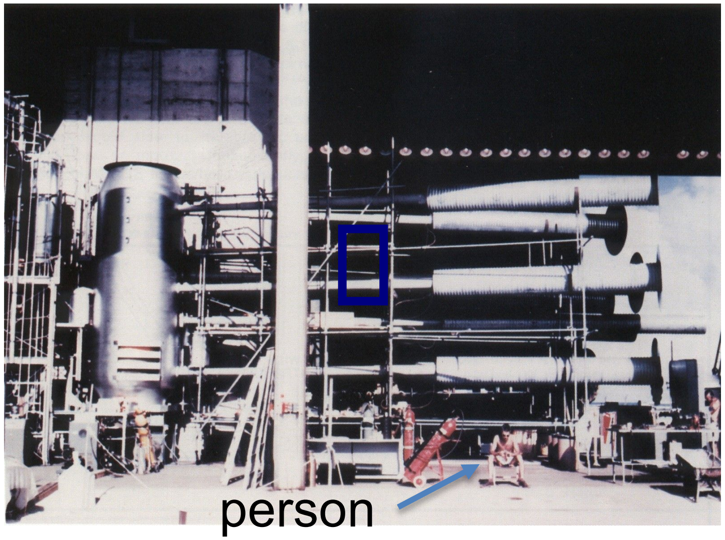
- Isotopes of lithium absorb neutrons resulting in the production of tritium

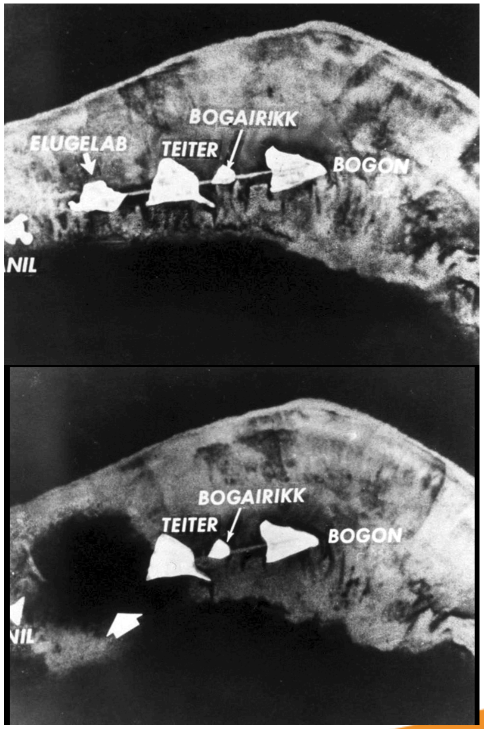
$${}^{6}_{3}\text{Li} + n \rightarrow T + {}^{4}_{2}\text{He} + 4.8\ \text{MeV} \qquad \text{exothermic}$$

$${}^{7}_{3}\text{Li} + n \rightarrow T + {}^{4}_{2}\text{He} + n - 2.5\ \text{MeV} \qquad \text{endothermic}$$

- Tritium can undergo subsequent fusion with deuterium
- Unlike tritium, lithium is a stable compound
- Also no need for cryogenic storage

Ivy/Mike – tested at Enewetak/Elugelab; 10.4 Mt

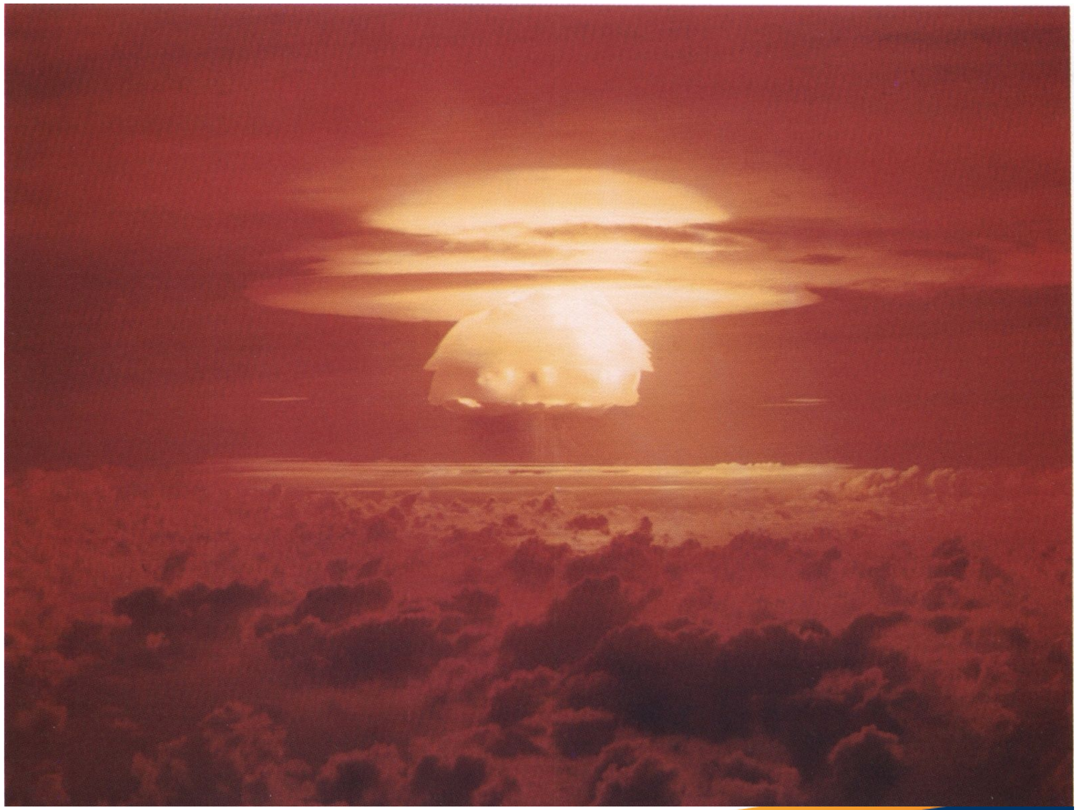




- “Experimental” thermonuclear device tested 10/31/52
- TN fuel was liquid deuterium
- Complex and bulky cryogenic equipment
- Vaporized Elugelab Island

Castle/Bravo - largest US test at 15 Mt

- Tested 2/28/1954 at Bikini
- Used lithium deuteride as a thermonuclear fuel
- Yield was more than twice the prediction; did not account for ^{7}Li breeding reactions
- Caused a lot of fallout, mainly due to last minute wind shift
- Fukuryu Maru fishing boat was symbol of contamination

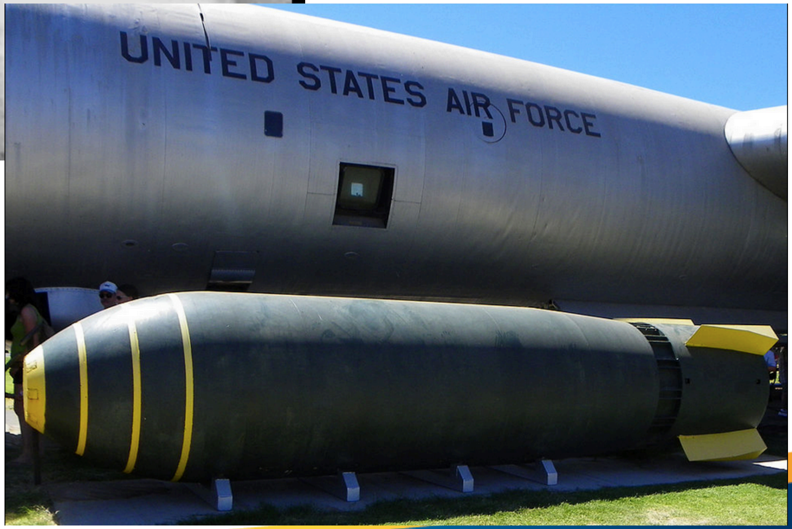


The 1950’s saw new types of weapons

- Concern in the US led to development of bombers capable of delivering very large weapons (B36) for “emergency capability”
- There was also a push to make the TN weapons smaller and lighter
- At the same time, weapons were being developed for different applications (torpedoes, missiles, anti-aircraft missiles, artillery, etc.)

Large bombs, larger planes

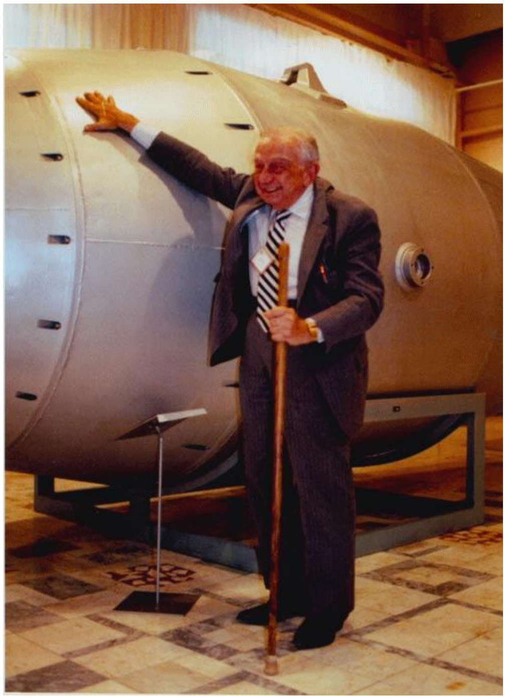
B-36: 162 feet long
230 foot wingspan



- B36 bomber and B17 bomb (41,000+ lbs, 25 ft)
- The B36 could carry two of these!!

Soviets: “Tsar Bomba” -- largest weapon detonation

- Soviet test near Novaja Zemlya on 30 October 1961
- Fired at: ~50 Mt
- Design yield: 100 Mt
- Blast scorched planes at some distance



Dr. Edward Teller (5’8”)
at Snezhinsk (C-70)

Tsar Bomba test – ~50 Mt

- “Tsar Bomba was largest test ever at ~50 Mt
- Some of material was inert – design was 100 Mt
- Was more of a political statement according to one of the designers that I talked to

Surface to Air missiles against bomber fleets

- In the 1950's there were concerns about Soviet bomber fleets making it to the US.
- Developed Surface to Air missiles to counter the threat
- While some missiles could be targeted at individual planes, nuclear tipped missiles could destroy many planes or cripple the crews
- These are pictures of Nike-Hercules missiles from Marin County California site.
- These missiles are deactivated, but still accountable under treaties

Nike Hercules missile

Nuclear weapons were on many devices

- Starting in the 1950’s there were many different types of nuclear-tipped weapons
  - Artillery
  - Torpedoes and depth charges
  - Cruise missiles
  - Air to air missiles (not shown)
  - Atomic demolition munitions
- Many were recognized as impractical and withdrawn

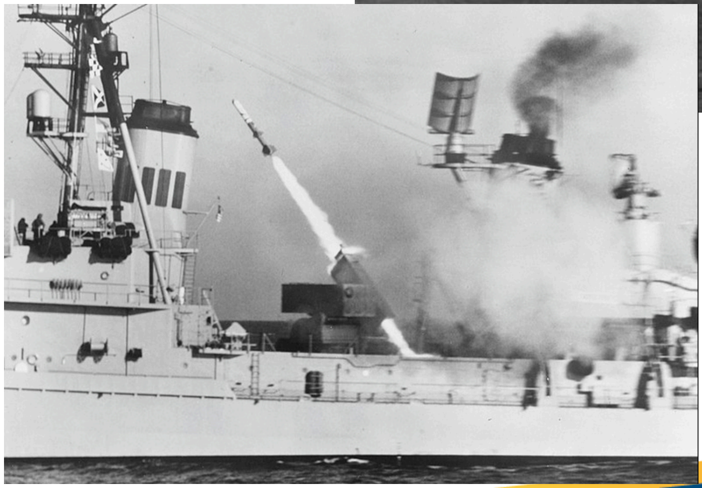
Specialty weapons: artillery

- 11 inch “Atomic cannon” developed
- W9 nuclear shell weighed ~800 lbs
- Grable test done 5/25/53
- Yield was ~15 kt

Specialty weapons: torpedoes

- US developed nuclear depth charges and torpedoes
- Depth charges around for a while
- Kill probability of two made torpedoes unattractive

Wahoo test

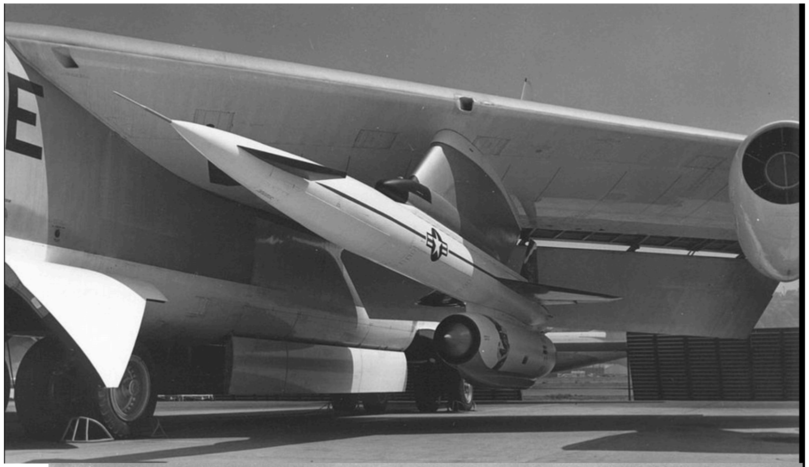


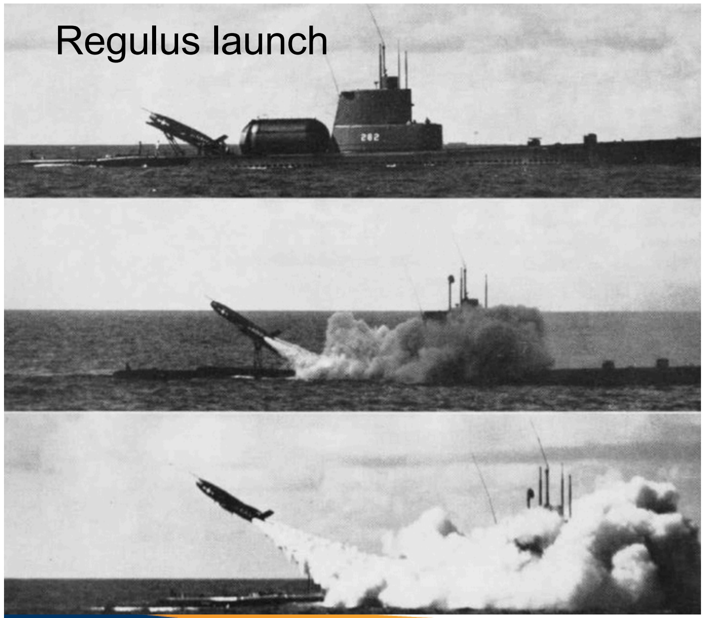
ASROC -- ASW

W45 nuclear torpedo

Specialty weapons: cruise missiles

- Hound dog and Regulus (W28 and B28, B36)




Regulus launch

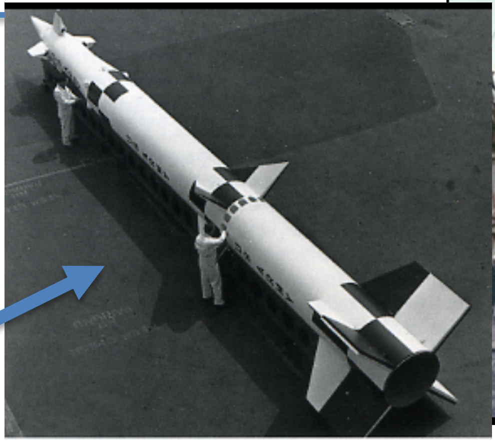
Regulus missile

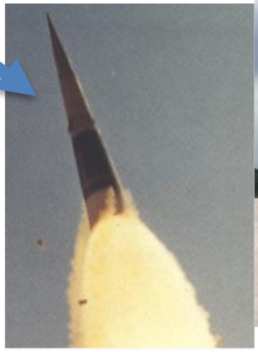
Hound Dog cruise missile

Specialty weapons: ABMs

- In the 1960’s there was a push by US and USSR to develop and deploy Anti-Ballstic Missiles (ABMs)
- The US version has Spartan (high altitude kill) and Sprint (close in kill) options
- Developed and deployed for one day in 1972
- ABM treaty came into force (withdrawal in 2002)

Cannikin test





Sprint launchers

Specialty weapons: “neutron bomb”

- Massive conventional numerical superiority of Warsaw Pact was big concern to NATO
- War planners wanted smaller weapons to kill enemy troops and tanks without obliterating all the cities of Europe
- Led to neutron bomb, where output was mostly neutrons and not blast
- Withdrawn in late 1980’s

T-72 tank

Atomic demolition munitions

- These include the so-called "suitcase nuke" (W54)
  - Size was ~11x16 inches and 51 lbs
  - Designed for demolitions during a Soviet invasion of Western Europe
- The W48 6-inch artillery shell is also quite small (85cm long, 54 kg)

H-912 transport container for Mk-54 SADM

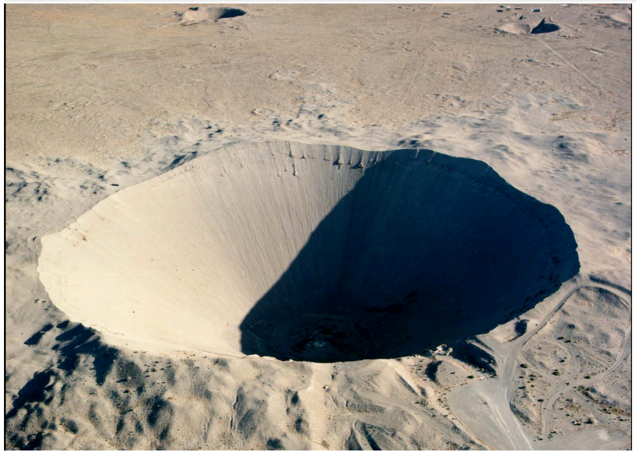
Not all nuclear devices were weapons

- Project Plowshare showcased peaceful uses of nuclear devices
- Also nuclear-powered rockets (won't discuss)

Project Plowshare: peaceful nukes

- In addition to specialty weapons, there were hopes of using nukes for other projects
- Rapid canal or harbor digging – one across Nicaragua was seriously considered
- An early version of fracking was tried several times (Soviets did this too)

Project Plowshare: cratering shots



Sedan: 104 kt
(414 m diameter; alluvium)

Schooner: 30 kt
(375 m diameter; basalt)

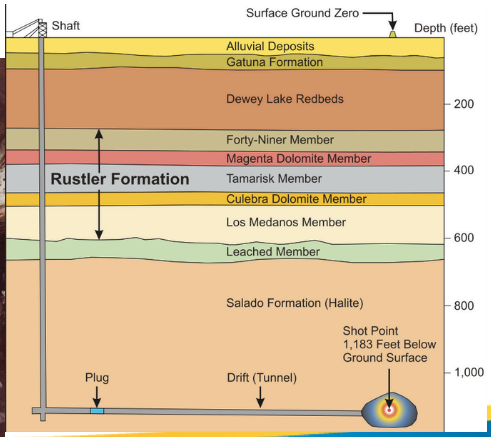
Buggy: 5x1 kt (261 m long)
Basalt

- Several cratering tests done at NTS
- Residual radioactivity and fallout doomed practical use

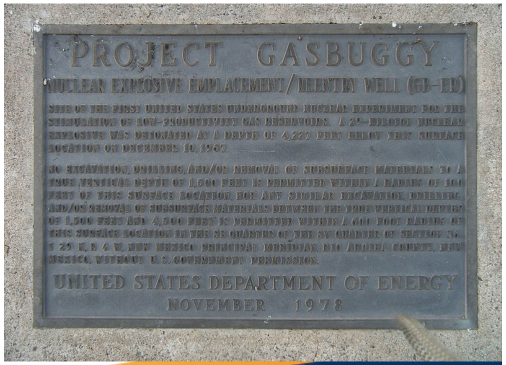
Project Plowshare: other shots

- Gnome was used to excavate a salt cavity near Carlsbad, NM
- Gasbuggy, Rulison and Rio Blanco were used in an early version of "fracking" to stimulate natural gas production
  - People did not like idea of contaminated gas
  - Irony is that some natural gas is naturally contaminated; companies clean it up

Gnome cavity: human for scale



Gasbuggy Shot near Dulce, NM



PROJECT GASBUGGY

NUCLEAR EXPLOSIVE EMPLACEMENT/REENTRY WELL (GB-ER)

SITE OF THE FIRST UNITED STATES UNDERGROUND NUCLEAR EXPERIMENT FOR THE STIMULATION OF LOW-PRODUCTIVITY GAS RESERVOIRS. A 29-KILOTON NUCLEAR EXPLOSIVE WAS DETONATED AT A DEPTH OF 4,227 FEET BELOW THIS SURFACE LOCATION ON DECEMBER 10, 1967.

NO EXCAVATION, DRILLING, AND/OR REMOVAL OF SUBSURFACE MATERIALS TO A TRUE VERTICAL DEPTH OF 1,500 FEET IS PERMITTED WITHIN A RADIUS OF 100 FEET OF THIS SURFACE LOCATION, NOR ANY SIMILAR EXCAVATION, DRILLING, AND/OR REMOVAL OF SUBSURFACE MATERIALS BETWEEN THE TRUE VERTICAL DEPTHS OF 1,500 FEET AND 4,500 FEET IS PERMITTED WITHIN A 600 FOOT RADIUS OF THIS SURFACE LOCATION IN THE SE QUARTER OF THE SW QUARTER OF SECTION 36, T 29 N, R 4 W, NEW MEXICO PRINCIPAL MERIDIAN, RIO ARRIBA COUNTY, NEW MEXICO, WITHOUT U.S. GOVERNMENT PERMISSION.

UNITED STATES DEPARTMENT OF ENERGY

NOVEMBER 1978

Modern weapons: the “Triad”

- Our current “Triad” has
  - Land-based ICBMs
  - Sea-launched SLBMs
  - Bomber carried bombs and cruise missiles
- Each has a distinct role

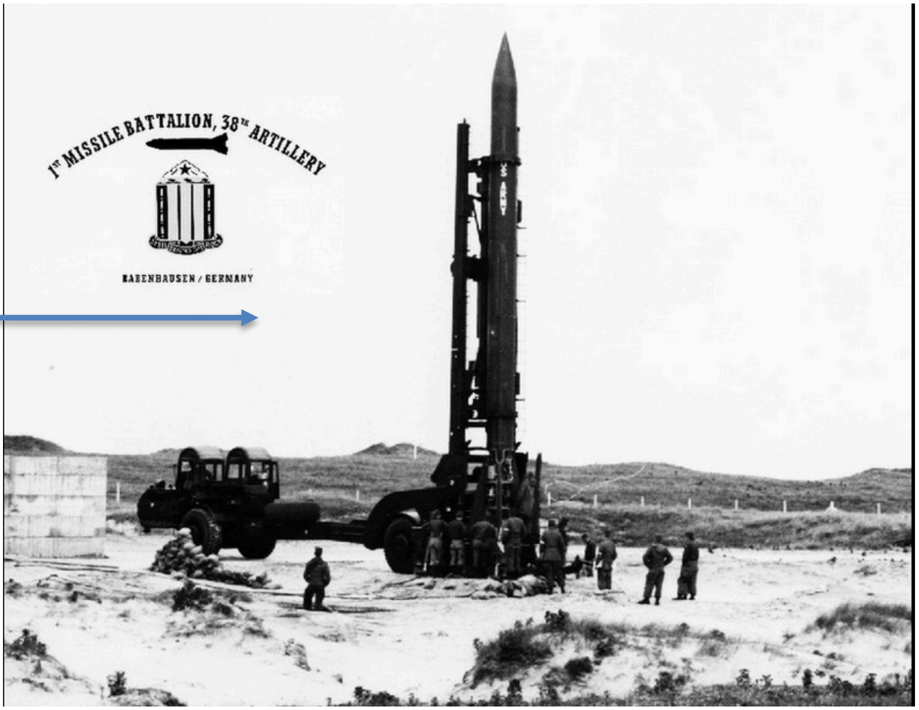
Ballistic Missiles

- US and Soviets got V2 missiles and scientists
- Both sides started with intermediate range, then intercontinental range missiles
- US then pushed towards submarine launched ballistic missiles – Soviets followed suit
- Started with 1 to 3 in the “sail”, then to 12 to 24

Soviet “Golf” class submarine

Short range ballistic missiles were the start

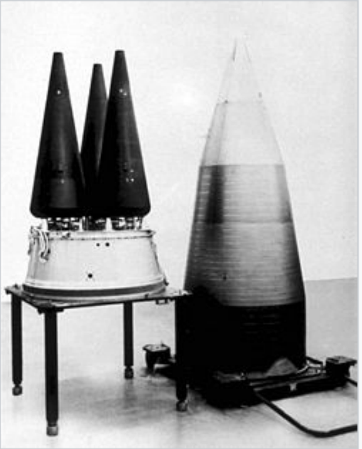
- Mk 7 warhead was 30 inches diameter and ~1700 lbs
- On Honest John (26 km) and Corporal (140 km) missiles
- Eventually moved to Intermediate Range Ballistic Missiles (IRBMs)



Pershing II
(in Europe)

ICBM’s

- Intercontinental Ballistic Missiles (ICBMs) are the land based arm of the “nuclear triad”
- Current missile is Minuteman III
- Previous missiles were Minuteman II and Peacekeeper
- The protected silos require a hit from a nuke to knock them out
- Cannot be recalled once launched



W78 warheads are contained inside the MK12-A reentry vehicles of the LGM-30G Minuteman III.

A Minuteman-III missile in its silo

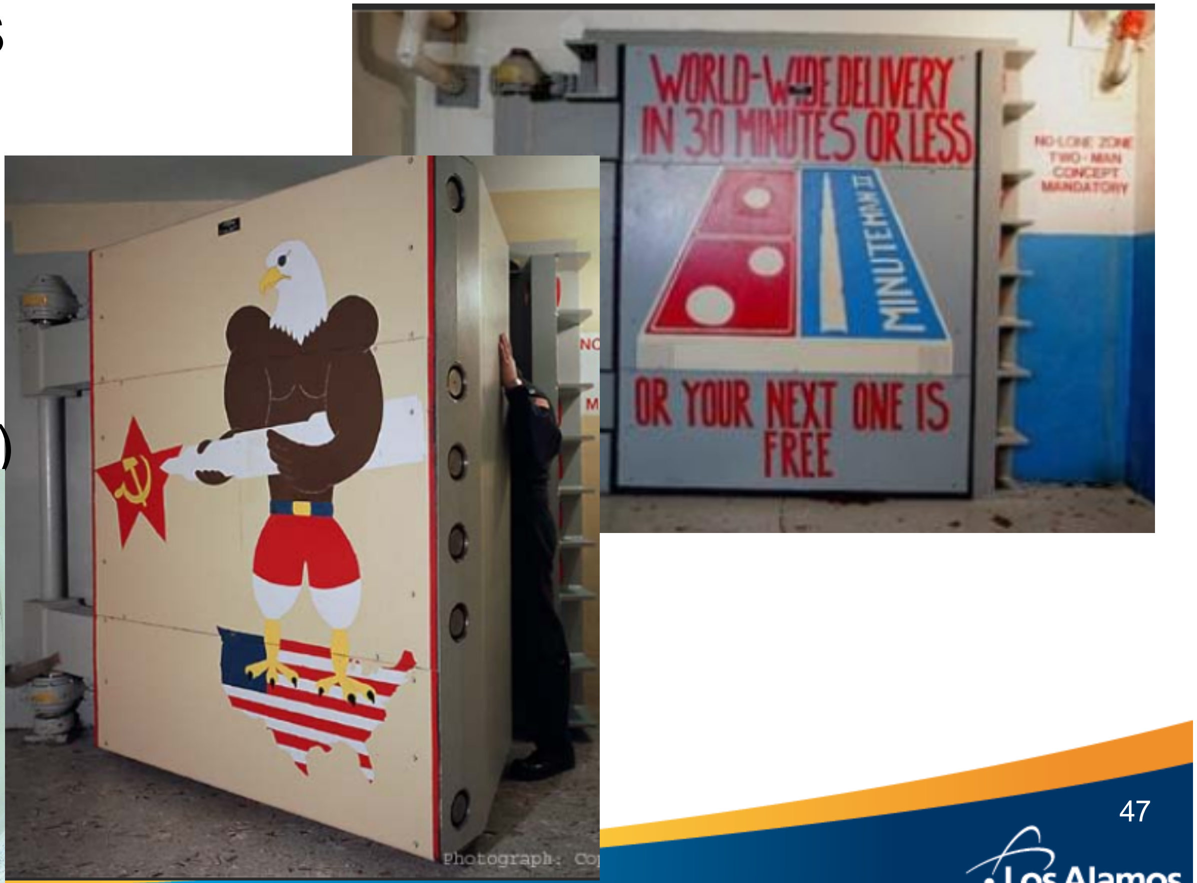
Minuteman-III

Missile launch facilities have some humor

- Several generations of ICBMS
- Start was liquid fuel rockets (Titan II)
- Cold War humor on Minuteman II blast doors
- One MMII is on display near Wall, SD (part of Park Service)

Titan

Minuteman II


WORLD-WIDE DELIVERY IN 30 MINUTES OR LESS
MINUTEMAN II
OR YOUR NEXT ONE IS FREE
NO-LONE ZONE TWO-MAN CONCEPT MANDATORY
Photograph: Co

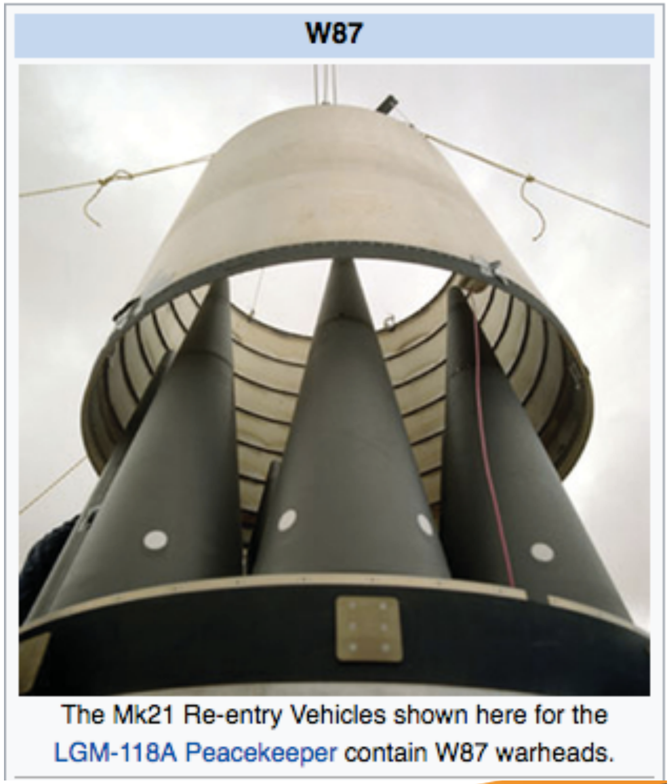
SLBM’s

- Submarine Launched Ballistic Missiles (SLBMs) are the sea based arm of the “nuclear triad”
- Current missile is Trident on Ohio-class submarines
- Submarines are very quiet, so can launch without warning
- Can reach anywhere in the world if needed
- Cannot be recalled once launched

USS Michigan

MIRV concept

- MIRV stands for “Multiple Independent Re-entry Vehicles”
- Considered “Destabilizing” since one missile could destroy many enemy missile launchers
- This really reinforced “Mutually Assured Destruction (MAD) doctrine”
- Led to SALT and then START treaties



W87

The Mk21 Re-entry Vehicles shown here for the LGM-118A Peacekeeper contain W87 warheads.

Bombers

- The airborne portion of the “triad”
- Currently, the B-2 would carry nuclear weapons
- The bombs are the B-61 and the B-83
- The B-2 and B52 can carry nuclear tipped cruise missiles as well
- Bombers can be recalled if necessary

B-2 bomber

B83

B61

ALCM

Successes

- Financial struggles of Soviet Union and realization that no one would win led to several treaties
- Intermediate range Nuclear Forces (INF) treaty removed a class of weapons
- SALT moved to START treaties
- Unfortunately, there has been backtracking

Some modern trends

- ABMs
- Some countries pushing low yield devices
  1. Use as "escalate to de-escalate" in a limited war
  2. Coupled with high accuracy, can limit collateral damage
- Challenge is to find ways to make such options unattractive

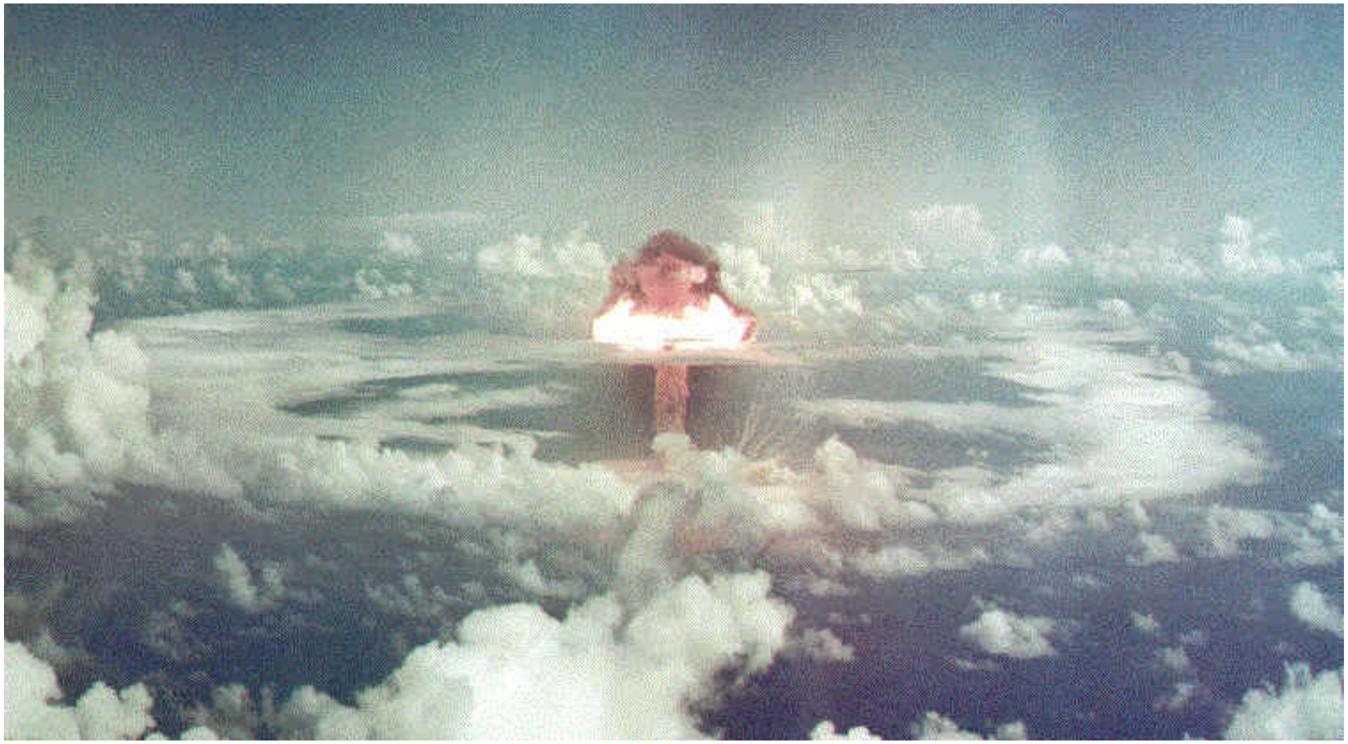
Conclusions

- Nuclear weapons were an outgrowth of the discovery of fission (and fusion)
- It was only a question of time to develop a weapon once the awesome energy of the nucleus was known
- Countries have developed nuclear weapons of many types
- Too much of a “big stick” for countries to get rid of

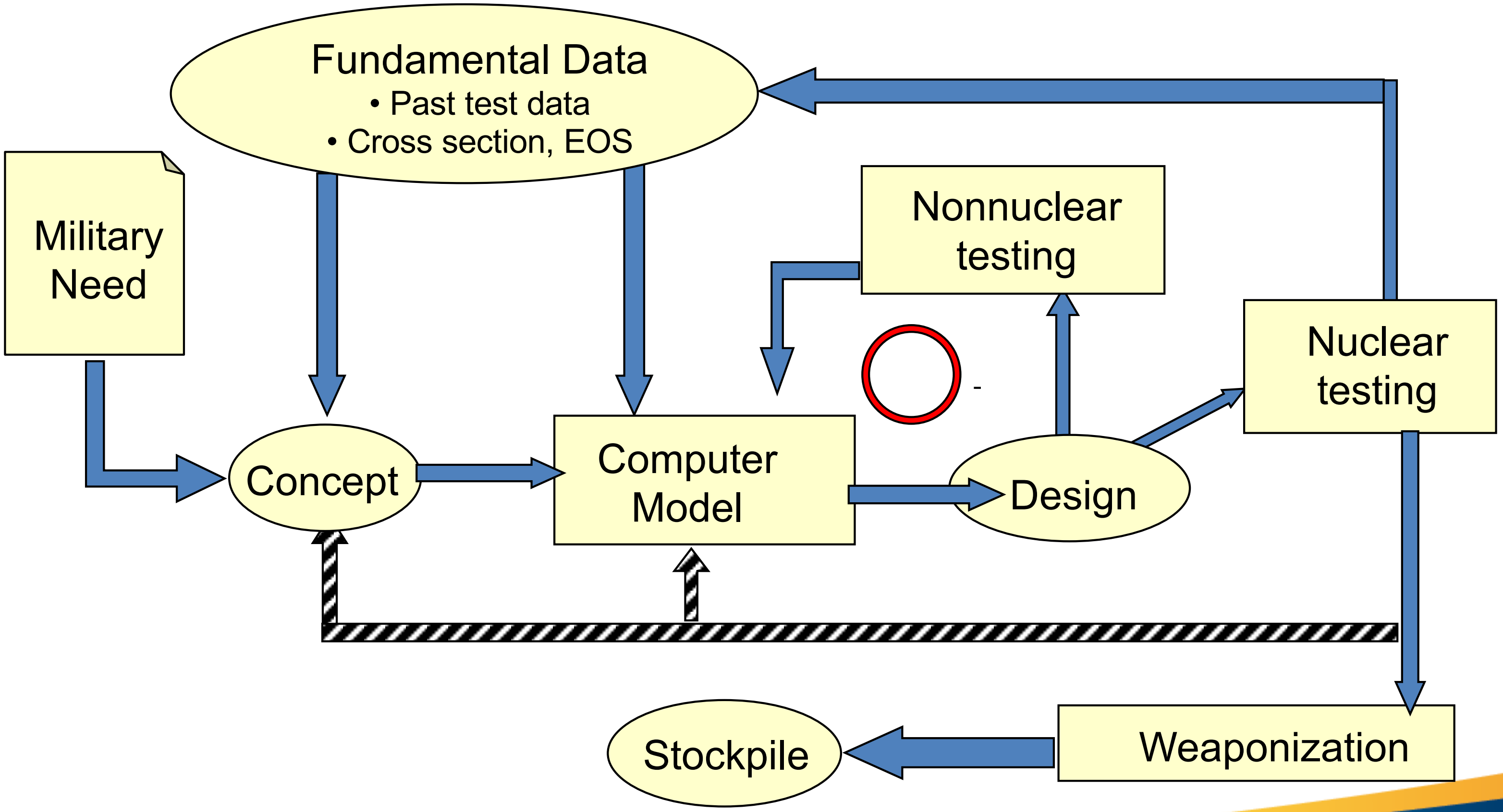
Thank you!
Questions?

Backup material

Ivy/King – tested on 11/15/52 at Enewetak; largest US fission only device (500 kt)



Traditional Design and Development



B-61 Nuclear Bomb (>4000 parts)